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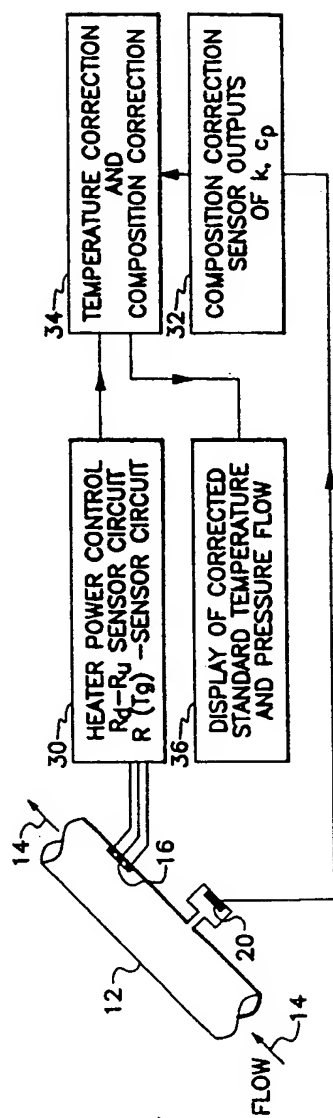(51) Int. Cl.^{5} : **G01F 15/02**

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(72) Inventor : **Bonne, Ulrich**
4936 Shady Oak Road
Minneapolis, Minnesota 55343 (US)
Inventor : **Kubislak, David**
1461 Heron Drive
Chanhassen, Minnesota 55317 (US)

(74) Representative : **Fox-Male, Nicholas Vincent**
Humbert
Honeywell Control Systems Limited Charles
Square
Bracknell Berkshire RG12 1EB (GB)

(54) Flowmeter fluid composition and temperature correction.

(57) To correct the flow measurment of a gaseous or liquid fluid of interest for changes in the composition and temperature of that fluid in a flowmeter of the hot element type, an uncorrected flow value signal for the fluid of interest in relation to a hot element sensor output is corrected by applying a correction factor to the flow value signal based on certain unique physical parameters of the fluid of interest which nominally include thermal conductivity, k, specific heat, c_p, and temperature, T.

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TEMPERATURE CORRECTION AND COMPOSITION CORRECTION

34

COMPOSITION CORRECTION SENSOR OUTPUTS OF k, c_p

32

HEATER POWER CONTROL $R_q - R_u$ SENSOR CIRCUIT $R(T_\theta)$ - SENSOR CIRCUIT

30

DISPLAY OF CORRECTED STANDARD TEMPERATURE AND PRESSURE FLOW

36

14

16

12

20

14

FLOW

14

BLOCK DIAGRAM OF PROPOSED
TEMPERATURE AND/OR PRESSURE
COMPENSATION FOR MB FLOW SENSORS

Fig. 1

CROSS REFERENCE TO RELATED APPLICATION

Reference is made to copending allowed application Serial No. 07/285,897 filed December 16, 1988 and assigned to the common assignee of the present application.

BACKGROUND OF THE INVENTION

The present invention relates to fluid flow measurement and, more particularly, addresses overcoming inaccuracies in flow measurement. The invention provides a method for eliminating errors in mass and volumetric (and energy) flow rates measured for primarily gaseous fluid with respect to temperature changes in the gaseous fluids.

Flow sensors that utilize a pair of thin film heat sensors and a thin film heater are known. An example of such a device is illustrated and described in U.S. Patent 4,501,144 to Higashi, et al. The thin film heat sensors may be arranged in a Wheatstone bridge so that the output of the bridge is representative of flow. These micro-anemometers or "microbridges" are produced using similar techniques to those used for producing integrated circuits and are thus quite inexpensive.

As will be described in greater detail herein, such microanemometers or microbridges are capable of quite accurate flow sensing when directly exposed to a stream of fluid flowing past them. In this manner, such a sensor can be used to directly measure the flow velocity of the fluid.

While such a sensing system can be used to approximately measure mass flow, a significant level of error has been experienced with respect to changes in composition of the measured fluid in prior devices using this system. Allowed patent application Serial No. 07/285,897 entitled "Flow Meter Fluid Composition Correction" and assigned to the same assignee as the present application, describes in detail a method of correcting gaseous fluid flow measurement for changes in composition. Applying the composition corrections provided in application Serial No. 07/285,897 will generally provide flow measurements accurate to within 10%. While this accuracy is sufficient for many nonprecision applications, there remain many precision applications that require a greater accuracy. Further investigation has resulted in the discovery of the algorithm of the present invention. The investigation showed that after applying the composition correction, there still remained an error due to the temperature difference of the gaseous fluid relative to the temperature of the calibration fluid.

For illustration purposes, errors due to temperature of about 0.2% per °C were observed when the temperature of the gaseous fluid varied about ± 10° from the 23°C calibration temperature. This error of approximately 5% for a 10° temperature difference is unacceptable for many precision gas flow measurement applications. Thus a need exists for a method to correct gas flow measurements for variations in the temperature of the flowing gas from the temperature of the calibration gas.

SUMMARY OF THE INVENTION

The present invention solves these needs and problems in the field of hot element (wire or film) gas flow measurements by providing a method which can be used to correct the measured flow for changes in both the composition of the gas and the temperature of the gas relative to the calibration gas composition and temperature.

The invention includes an equation for determining a gauge correction (C_G) which is applied to a measured gauge output (G) of the microbridge (MB) and an equation for determining a volumetric flow correction (C_V) which is applied to the measured volumetric flow (V).

$$V = V(G) \quad (1)$$

The C_G and C_V corrections are determined using preferred equations of the form:

$$C_G = (k_e/k_{co})^{n1}(c_{pe}/c_{pco})^{n2}(T_e/T_c)^{n3} \quad (2)$$
$$C_V = (k_e/k_{co})^{n4}(c_{pe}/c_{pco})^{n5}(T_e/T_c)^{n6} \quad (3)$$

where:

k_e = thermal conductivity of the measured gas at the environment or calibration temperature and pressure

k_{co} = thermal conductivity of the calibration gas at the calibration gas at the calibration temperature and pressure

c_{pe} = specific heat of the measured gas at the environment or calibration temperature and pressure

c_{pco} = specific heat of the claibration gas at the calibration temperature and pressure

T_e = absolute temperature of the measured gas environment

T_c = absolute temperature of the calibration gas

n_1 through n_6 constants determined during a calibration process

While the influence of pressure on k and c_p is minor under most conditions, applications using high press-

ures i.e. over 100 psi (or over 7 atmospheric) would experience such influences, and would require the full power of equations (2) and (3).

After constants n_1 through n_6 have been determined in the calibration procedure, the equation for C_G and C_V may be used to determine the appropriate C_G and C_V for a gas flow measurement when the gas has a thermal conductivity k_e, a specific heat c_{pe} and a temperature T_e.

The use of the C_G and C_V correction is explained as follows. A measured volumetric flow, V_c, is determined according to:

$$V = f(G_c) \quad (1)$$

where G = microbridge output or gauge signal and

$$G_c = G/C_G$$

$f(G_c)$ = polynomial function of G_c

The measured volumetric flow is then corrected to a corrected volumetric flow (V_c) according to:

$$V_c = V/C_V$$

The present invention includes the steps of a calibration process and of a user process. The calibration process begins by experimentally determining microbridge output values for known volumetric flows for several gases at several temperatures. Such data may be represented graphically as calibration curves, V = f(G).

Each calibration curve is then compared to one specially selected or reference calibration curve. Correction factors C_G for the microbridge gauge output signal and correction factors C_V for the volumetric flows are experimentally determined in such a way as to achieve a best match between the reference calibration curve and all other curves.

Values of thermal conductivity, specific heat and temperature for each of the gases at each of the temperatures are either theoretically determined from known thermodynamic data or measured. These values are normalized with respect to the reference condition.

To complete the calibration process, the algorithm of the present invention is then derived to relate the experimentally determined correction factors C_G and C_V to the normalized values of k, cp and T. An algorithm is then available to a user for use to correct a gas flow measurement for composition and temperature changes.

In the typical user process a gas flow measurement is being made. A measured microbridge output signal, G, is obtained. Using the thermal conductivity, specific heat and temperature also obtained with the microbridge during the gas flow measurement and the formula of the invention a gauge correction factor, C_G is determined. A corrected gauge output value, G_c, is determined by dividing the measured gauge output, G by the correction factor C_G.

The corrected gauge output, G_c, is then used in an equation that calculates measured gas flow, v. This equation is of the form:

$$V = a_0 + a_1 G^{m1} + a_2 G^{m2} + a_3 G^{m3} \dots = V(G) \quad (1)$$

where m_i and a_i = constants which represent the reference calibration curve

After the measured volumetric flow, V, is determined, it must be corrected by a correction factor, C_V.

C_V is determined by using the algorithm of the invention. The corrected volumetric flow, V_c, is then determined by dividing V by C_V.

DESCRIPTION OF THE DRAWINGS

Figure 1 is a diagrammatic representation of a method of composition and temperature compensation of gas flow measurements in accordance with the present invention.

Figure 2 is a plot of the microbridge output signals as a function of volumetric flows for gas flow measurements using methane at temperatures at 9.2° C, 23° C and 35.3° C.

Figure 3 is a plot of the error in percent of a microbridge flow measurement versus volumetric flow when the correction factors of the present invention are not used. The gas is methane at temperatures of 9.2° C, 23° C and 35.3° C.

Figure 4 is a plot of the microbridge flow measurement error as a function of volumetric flow after the corrections of the present invention have been applied. The gas is methane at temperatures of 9.2° C, 23° C and 35.3° C.

Figure 5 is a plot of the microbridge flow measurement error in percent as a function of volumetric flow with the corrections of the present invention applied. The gases are ethane at 9.2° C and 34.8° C, and nitrogen at 9.4° C and 35.2° C.

Figure 6 is a plot of the microbridge flow measurement error only in percent as a function of volumetric flow for methane at 23° C, ethane at 22.5° C and nitrogen at 21.9° C.

Figure 7 is a plot of the microbridge flow measurement error in percent as a function of the mass flow for methane at 9.2° C, 23° C and 35.3°, ethane at 22,5° C and nitrogen at 21.9° C.

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DESCRIPTION OF THE INVENTION

Figure 1 illustrates one embodiment of applicant's invention of a method of temperature compensation for microbridge flow sensors. The system is depicted as a section of pipe, gas pipe, conduit or the like 12 through which a gaseous fluid 14 of interest is flowing.

A microbridge or microanemometer sensor package for sensing flow through the system is shown generally at dynamic flow location 16. It includes an individual microbridge sensor for dynamic sensing of fluid flow. Semiconductor chip sensors or microbridges of the class described are treated in a more detailed manner in one or more of patents such as 4,478,076, 4,478,077, 4,501,144, 4,555,939, 4,651,564 and 4,683,159 all of common assignee with the present invention. To the extent necessary, additional details with respect to the microbridge sensors are incorporated by reference from these cited documents.

Microbridge sensors typically require heated power control circuitry as identified in block 30. In addition, circuitry is needed for monitoring the difference in resistance of a resistor (R_d) located downstream of the heated elements and a resistor (R_u) located upstream of the heated elements as identified in block 30.

In accordance with the present invention, a resistive temperature sensing element R is required for the purpose of measuring the temperature T_g of the gas. Resistor R, is indicated in Figure 1 as being located at the dynamic flow location 16. Resistor R is a resistor element which may be located on the microbridge chip.

In accordance with allowed related application Serial No. 07/285,897, a second microbridge location called a static microbridge location is indicated at 20. The method of determining the composition correction based on thermal conductivity, k, and specific heat, c_p, identified in block 32 of Figure 1 is disclosed in the allowed application. An alternate location for resistor R is at static location 20.

Figure 1 illustrates that information from block 32 on composition correction and information from block 30 including gas temperature information is provided to block 34. After calculations relating to flow and composition and temperature corrections, the flow at standard temperature and pressure is displayed as identified in block 36.

Figure 2 is a plot of the measured microbridge output or gauge G versus the standard volume flow of methane at temperatures of 9.2° C, 23° C and 35.3° C. Ideally, the plots for the three temperatures would be identical. Actually, the error due to temperature is so small that it is not readily apparent from Figure 2. However, if only the error is plotted as in Figure 3, it is apparent that the error of the 9.3° C measurement and the 35.2° C measurement relative to the 23° C measurement are significantly greater than ± 1%.

This invention teaches a method of correcting for the effects of temperature differences between the calibration gas at the time of the calibration and the test gas at the time of device use in the following overall compensation equation.

$$V_C = V(G/C_G) \times (1/C_V) \quad (1a)$$

Where

V = Volumetric flow rate as a function of G or G/C_G

G = the R_d - R_u microbridge output or gauge signal

C_G = correction of gauge output signal

C_V = correction of measured volumetric flow

Equation 1a corrects for temperature effect errors by causing a y-axis shift of the calibration curve with the C_G correction factor and for temperature effects by causing an x-axis shift of the calibration curve with the C_V correction factor.

A preferred complete temperature correction is of the following form:

$$C_G = (k_g/k_{c0})^{n1}(c_{pg}/c_{pc0})^{n2}(T_g/T_c)^{n3} \quad (2)$$
$$C_V = (k_g/k_{c0})^{n4}(c_{pg}/c_{pc0})^{n5}(T_g/T_c)^{n6} \quad (3)$$

where: n_1 through n_6 = constants determined by

the calibration procedure

subscript e = during experiment or test

subscript c = during calibration

subscript o = for calibration gas (generally

air or methane)

k = thermal conductivity as

measured by the composition

correction MB

c_p = either specific heat in

pressure independent units of,

e.g. cal/(mol C) or its

temperature derivative, also

pressure independent

T = absolute temperature

It will be understood that other more general equations may be used to recognize the physics of the micro-bridge sensor structure. Particularly the thermal conductivity and specific heat of not only the gas, but also of solid substances of the sensor may be considered. Other more general forms of equation 2 are shown below:

$$1/C_G = \{(A_0 + k_e)/(A_0 + k_{co})\}^{n_1}\{(B_0 + c_{pe})/ \qquad (2a)$$
$$(B_0 + c_{pco})\}^{n_2}\{T_e/T_c\}^{n_3}$$

$$1/C_G = \{(A_0 + A_1 k_e^{m_1} + A_2 k_e^{m_2} + \ldots)/ \qquad (2b)$$
$$(A_0 + A_1 k_{co}^{m_1} + A_2 k_{co}^{m_2} + \ldots)\}^{n_1}$$
$$\{(B_0 + B_1 c_{pe}^{P_1} + B_2 c_{pe}^{P_2} + \ldots)/$$
$$(B_0 + B_1 c_{pco}^{P_1} + \ldots)\}^{n_2}\{T_e/T_c\}^{n_3}$$

where constants A_i, B_i and m_i are determined during the calibration procedure and allow for recognition of the thermal conductivity and specific heat of substances other than the gas. More general forms of equation 3 are shown below:

$$1/C_V = ((C_0 + k_e)/(C_0 + k_{co}))^{n_4}((D_0 + c_{pe})/ \qquad (3a)$$

$$(D_0 + c_{pco}))^{n_5}(T_e/T_c)^{n_6}$$

$$1/C_V = ((C_0 + C_1 k_e^{q_1} + C_2 k_e^{q_2} + \ldots)/ \qquad (3b)$$

$$(C_0 + C_1 k_{co}^{q_1} + C_2 k_{co}^{q_2} + \ldots))^{n_4}$$

$$((D_0 + D_1 c_{pe}^{r_1} + \ldots)/(D_0 + D_1 c_{pco}^{r_1} + \ldots))^{n_5}$$

$$(T_e/T_c)^{n_6}$$

where constants C_i, D_i, q_i and r_i are determined during the calibration process and allow for recognition of the thermal conductivity and specific heat of substances other than the gas, and other heat transfer processes such as radioactive ones.

The implementation of the correction provided by the present invention will now be explained.

For illustration purposes we will use methane, ethane and nitrogen as the gases of interest and microbridge calibration data at approximately 5° C, 23° C and 35° C. It is understood that those are merely examples and the invention applies to other gases and calibration data at other temperatures.

It is further understood that while this invention is described with respect to volumetric gas flow measurements, it is also applicable to mass flow measurements or energy flow measurements. For mass flow measurements, the uncorrected mass flow is designated M and the corrected mass flow is designated M_C. For energy flow measurements, the uncorrected energy flow is designated E and the corrected energy flow is designated E_C. For mass flow and energy flow measurements, the gauge correction (C_G) remains the same, but the mass correction is designated as C_M and the energy correction is designated as C_E.

CALIBRATION PROCESS

This process includes the following steps:

1) Determination of microbridge calibration curves for several gases of interest at several temperatures. Equations (2) and (3) for C_G and C_V, respectively, require for each the determination of 3 unknown exponents. Therefore, at least 3 calibration curves must be determined. The microbridge calibration curve is a plot of microbridge output values versus standard volume flows.

2) Selection of one gas, e.g. methane at 23° C as the reference operating condition and fitting the best possible calibration curve to the microbridge output values. This establishes a reference calibration curve for methane at 23° C, V(G).

3) Determining the correction factors C_G and C_V for other temperatures of methane and for other gases at other temperatures. This is accomplished by comparing the other calibration curves to the reference calibration curve and determining the gauge correction factors C_G needed to cause the necessary y-axis shifts and the volumetric correction factors C_V needed to cause the necessary x-axis shifts to allow the other calibration curves to conform to the chosen reference curve, i.e. the methane calibration curve at 23° C. The determination may be by visual comparison of the calibration curves or by using known data processing techniques.

4) Calculation from thermodynamic reference data or from measured data the values of k/k_o, c_p/c_{po} and T/T_o for the other gases and other temperatures.

5) Use the C_G and C_V values experimentally determined for other gases and temperatures and the normalized k, c_p and T values calculated, and solve for the best n_1 through n_6 in equations (2) and (3).

Equations (2) and (3) can then be used with the determined n_1 through n_6 to determine C_G and C_V for any gas at any temperature.

Table 1 shows selected representative values obtained for methane, ethane and nitrogen when the described calibration process was used.

Figure 4 illustrates the results of applying the temperature correction of the present invention to methane flow measurements at gas temperatures of 9.2° C, 23° C and 35.3° C. A very significant improvement over Figure 3 is noted with the error at flow above 30 liters per hour L/h being within about ± 1%.

Figure 5 illustrates the applicability of applicant's invention to gases significantly different than methane such as ethane and nitrogen.

Applicant has disclosed a method for correcting for the composition and temperature of a gas in order to

achieve a corrected volumetric gas flow measurement.

It will be apparent to those skilled in the art that this same methodoly used to achieve volumetric flow corrections may be used to achieve mass flow corrections; values of n_4, n_5 and n_6 were found to need adjustment, while n_1-n_3 required none.

Figure 7 illustrates the application of applicant's invention to mass flow measurements of methane, ethane and nitrogen. It will be noted that at flow rates above 100 g/h the error is generally less than ± 1%.

It will further be appreciated to those skilled in the art that the same methodology used to achieve volumetric flow corrections may be used to achieve energy flow corrections for certain groups of like combustible fluids.

In accordance with the foregoing description, applicant has developed a gas composition and gas temperature correction method that will provide very accurate gas flow measurements. Applicant's invention is applicable to volumetric flow measurements, mass flow measurements or energy flow measurements. Applicant's invention was accomplished by the recognition and solution of a long standing problem in gas flow measurements. Applicant's invention may readily be incorporated into those gas flow measurement applications requiring precision measurement.

TABLE 1

GAS	TEMPERATURE $^{\circ}C$	
CH_4	23°	$C_G = 1$
(Methane)		$C_V = 1$
CH_4	9.2°	$C_G = 0.9847$
		$C_V = 1.0299$
CH_4	35.3°	$C_G = 1.0132$
		$C_V = 0.9753$
C_2H_4	22.5°	$C_G = 0.9819$
(Ethane)		$C_V = 2.1588$
C_2H_4	9.2°	$C_G = 0.9686$
		$C_V = 2.2394$
C_2H_4	34.8°	$C_G = 0.9939$
		$C_V = 2.0918$
N_2	22.9°	$C_G = 1.0169$
(Nitrogen)		$C_V = 1.0321$
N_2	9.4°	$C_G = 1.0017$
		$C_V = 1.0601$
N_2	35.2°	$C_G = 1.0327$
		$C_V = 1.0046$

n_1	n_2	n_3
-0.015331	-0.060124	0.387617
n_4	n_5	n_6
-0.85033	0.9845898	0.027236

Claims

1. A method for compensating the flow measurement of a gaseous fluid of interest for changes in the composition, pressure and temperature of that fluid in a flowmeter having a first dynamic microbridge exposed to the flow and producing a flow-related output signal, the method characterised by the steps of:

   (A) obtaining an uncorrected dynamic microbridge sensor output (G) for the fluid of interest;

   (B) obtaining the specific heat (c_{pe}) thermal conductivity (k_e) and temperature (T_e) of the fluid of interest;

   (C) applying a gauge correction factor (C_G) to G to obtain a corrected sensor output (G_c), said C_G being determined according to a known relationship among values of specific heat (C_{pe}) thermal conductivity (k_e) and temperature (T_e) of the fluid of interest normalised with respect to a reference gas;

   (D) obtaining an uncorrected volumetric flow value (V) for the fluid of interest in relation to the corrected sensor output, G_c;

   (E) applying a volumetric correction factor (C_V) to the flow value (V) to obtain the corrected volumetric flow value (V_C), C_V being determined according to a known relationship, among values of specific heat (C_{pe}), thermal conductivity (k_e) and temperature (T_e) of the fluid of interest normalised with respect to the reference gas.

2. A method according to Claim 1 characterised in that the gauge correction factor is determined according to a relationship selected from:

$$C_G = (k_e/k_{co})^{n1}(c_{pe}/c_{pco})^{n2}(T_e/T_c)^{n3}$$

or

$$1/C_G = \{(A_O + k_e)/(A_O + k_{co})\}^{n1}\{B_O + c_{pe})/(B_O + c_{pco})\}^{n2} \{T_e/T_c\}^{n3}$$

or

$$1/C_G = \{(A_O + A_1 k_e{}^{m1} + A_2 k_e{}^{m2} + ...) /$$
$$(A_O + A_1 k_{co}{}^{m1} + A_2 k_{co}{}^{m2} + ...)\}^{n1}$$
$$\{(B_O + B_1 c_{pe}{}^{p1} + B_2 c_{pe}{}^{p2} + ...)/$$
$$(B_O + B_1 c_{pco}{}^{p1} + ...)\}^{n2}\{T_e/T_c\}^{n3}$$

and the volumetric correction factor (C_V) is determined according to a relationship selected from:

$$C_V = (k_e/k_{co})^{n4}(c_{pe}/c_{pco})^{n5}(T_e/T_c)^{n6}$$

or

$$1/C_V = \{(C_O + k_e)/(C_O + k_{co})\}^{n4}\{D_O + c_{pe})/(D_O + c_{pco})\}^{n5} \{T_e/T_c\}^{n6}$$

or

$$1/C_V = \{(C_O + C_1 k_e{}^{q1} + C_2 k_e{}^{q2} + ...)/$$
$$(C_O + C_1 k_{co}{}^{q1} + C_2 k_{co}{}^{q2} + ...)\}^{n4}$$
$$\{(D_O + D_1 c_{pe}{}^{r1} + ...)/(D_O + D_1 c_{pco}{}^{r1} + ...)\}^{n5}$$
$$\{T_e/T_c\}^{n6}$$

Where:

n_1 through n_6, A_i, B_i, m_i, C_i,

D_i, q_i, and r_i = constants determined by the calibration process, and

k_{co}, c_{pco} and Tc = thermal conductivity, specific heat and temperature of the calibration gas.

3. A method according to Claim 1 or 2 characterised in that the gauge correction factor is determined according to the relationship:

$$C_G = (k_e/k_{co})^{n1}(c_{pe}/c_{pco})^{n2}(T_e/T_c)^{n3}$$

and the volumetric correction factor C_V is determined according to the relationship:

$$C_V = (k_e/k_{co})^{n4}(c_{pe}/c_{pco})^{n5} (T_e/T_c)^{n6}$$

and n_1 through n_6, respectively, are approximately equal to:

- 0.015331

- 0.060124
  0.387617

- 0.85033
  0.9845898
  0.027236

4. A method for compensating the mass flow measurement of a gaseous fluid of interest for changes in the composition, pressure and temperature of that fluid in a flowmeter having a first dynamic microbridge exposed to the flow and producing a flow-related output signal, the method characterised by the steps of:

(A) obtaining an uncorrected dynamic microbridge sensor output (G) for the fluid of interest;

(B) obtaining the specific heat (c_{pe}) thermal conductivity (k_e) and temperature (T_e) of the fluid of interest;

(C) applying a gauge correction factor (C_G) to G to obtain a corrected sensor output (G_C), said C_G being determined according to a known relationship among values of specific heat (c_{pe}) thermal conductivity (k_e) and temperature (T_e) of the fluid of interest normalized with respect to a reference gas;

(D) obtaining an uncorrected mass flow value (M) for the fluid of interest in relation to the corrected gauge output (G_C);

(E) applying a mass correction factor (C_M) to the mass flow value to obtain the corrected mass flow value (M_C), C_M being determined according to a known relationship, among values of specific heat (c_{pe}), thermal conductivity (k_e) and temperature (T_e) of the fluid of interest normalized with respect to the reference gas.

5. A method according to Claim 4 characterised in that the gauge correction factor is determined according to a relationship selected from:

$$C_G = (k_e/k_{co})^{n1}(c_{pe}/c_{pco})^{n2}(T_e/T_c)^{n3}$$

or

$$1/C_G = \{(A_O + k_e)/(A_O + k_{oc})\}^{n1}\{B_O + c_{pe})/(B_O + c_{pco})\}^{n2}\{T_e/T_c\}^{n3}$$

or

$$1/C_G = \{(A_O + A_1 k_e{}^{m1} + A_2 k_e{}^{m2} + \ldots)/$$
$$(A_O + A_1 k_{co}{}^{m1} + A_2 k_{co}{}^{m2} + \ldots)\}^{n_1}$$

$$\{(B_O + B_1 c_{pe}{}^{P1} + B_2 c_{pe}{}^{P2} + \ldots) /$$
$$(B_O + B_1 c_{pco}{}^{P1} + \ldots)\}^{n_2}\{T_e/T_c\}^{n_3}$$

and the mass correction factor (C_M) is determined according to a relationship selected from:

$$C_M = (k_e/k_{co})^{n4}(c_{pe}/c_{pco})^{n5}(T_e/T_c)^{n6}$$

or

$$1/C_M = (C_O + k_e)/(C_O + k_{co})^{n4}\{(D_O + c_{pe})/(D_O + c_{pco})\}^{n5} \{T_e/T_c\}^{n6}$$

or

$$1/C_M = \{(C_O + C_1 k_e{}^{q1} + C_2 k_e{}^{q2} + \ldots)/$$
$$(C_O + C_1 k_{co}{}^{q2} + C_2 k_{co}{}^{q2} + \ldots)\}^{n_4}$$

$$\{(D_O + D_1 c_{pe}{}^{r1} + \ldots)/(D_O + D_1 c_{pco}{}^{r1} + \ldots)\}^{n_5}$$

$$\{T_e/T_c\}^{n_6}$$

Where:
n_1 through n_6, A_i, B_i, m_i, c_i,
D_i, q_i, and r_i = constants determined by the calibration process, and
K_{co}, c_{pco} and T_c = thermal conductivity, specific heat and temperature of the calibration gas.

6. A method for compensating the energy flow measurement of a gaseous fluid of interest for changes in the composition, pressure and temperature of that fluid in a flowmeter having a first dynamic microbridge exposed to the flow and producing a flow-relating output signal, the method characterised by the steps of:
   (A) obtaining an uncorrected dynamic microbridge sensor output (G) for the fluid of interest;
   (B) obtaining the specific heat (c_{pe}) thermal conductivity (k_e) and temperature (T_e) of the fluid of interest;
   (C) applying a gauge correction factor (C_G) to G to obtain a corrected sensor output (G_C), said C_G being determined according to a known relationship among values of specific heat (c_{pe}) thermal conductivity (k_e) and temperature (T_e) of the fluid of interest normalized with respect to a reference gas;
   (D) obtaining an uncorrected energy flow value (E) for the fluid of interest in relation to the corrected gauge output (G_C) ;
   (E) applying an energy correction factor (C_E) to the flow value to obtain the corrected energy flow value, (E_C), C_E being determined according to a known relationship, among values of specific heat (c_{pe}), thermal conductivity (k_e) and temperature (T_e) of the fluid of interest normalized with respect to the reference gas.

7. A method according to Claim 6 characterised in that the gauge correction factor is determined according to a relationship selected from:

$$C_G = (k_e/k_{co})^{n1}(c_{pe}/c_{pco})^{n2}(T_e/T_c)^{n3}$$

or

$$1/C_G = \{(A_O + k_e)/(A_O + k_{co})\}^{n1}\{B_O + c_{pe})/(B_O + c_{pco})\}^{n2}\{T_e/T_c\}^{n3}$$

or

$$1/C_G = \{(A_O + A_1 k_e^{m1} + A_2 k_e^{m2} + \ldots)/$$

$$(A_O + A_1 k_{co}^{m1} + A_2 k_{co}^{m2} + \ldots)\}^{n1}$$

$$\{(B_O + B_1 c_{pe}^{p1} + B_2 c_{pe}^{p2} + \ldots)/$$

$$(B_O + B_1 c_{pco}^{p1} + \ldots)\}^{n2}\{T_e/T_c\}^{n3}$$

and the energy correction factor (C_E) is determined according to a relationship selected from:

$$C_E = (k_e/k_{co})^{n4}(c_{pe}/c_{pco})^{n5}(T_e/T_c)^{n6}$$

or

$$1/C_E = \{(C_O + k_e)/(C_O + k_{co})\}^{n4}\{(D_O + c_{pe})/(D_O + c_{pco})\}^{n5}\{T_e/T_c\}^{n6}$$

or

$$1/C_E = \{(C_O + C_1 k_e^{q1} + C_2 k_e^{q2} + \ldots)/$$

$$(C_O + C_1 k_{co}^{q1} + C_1 k_{co}^{q2} + \ldots)\}^{n4}$$

$$\{(D_O + D_1 c_{pe}^{r1} + \ldots)/(D_O + D_1 c_{pco}^{r1} + \ldots)\}^{n5}$$

$$\{T_e/T_c\}^{n6}$$

Where:
n_1 through n_6, A_i, B_i, m_i, c_i,
D_i, q_i, and r_i = constants determined by the calibration process, and
K_{co}, c_{pco} and T_c = thermal conductivity, specific heat and temperature of the calibration gas.

8. A method according to any preceding Claim, characterised in that c_{pe}, k_e and T_e are determined by a second microbridge in relatively static communication with said fluid of interest.

9. A method according to any preceding Claim characterised in that said C_G determined in step (C) is determined according to a known relationship among variables selected from the group consisting of specific heat (c_{pe}), the differential of specific heat with respect to temperature (dc_{pe}/dT), thermal conductivity (k_e), the differential of thermal conductivity with respect to temperature (dk_e/dT), density, viscosity, speed of sound, optical absorption or diffusibility.

10. A method according to any preceding Claim characterised in that said step (C) of determining C_G is omitted and C_G is set equal to unity.

11. Apparatus for compensating the flow measurement of a gaseous fluid of interest for changes in the composition, pressure and temperature of that fluid in a flowmeter having a first dynamic microbridge exposed to the flow and producing a flow-related output signal, the apparatus characterised by operating according to the method of any of the preceding claims.

12. Apparatus for compensating the flow measurement of a gaseous fluid of interest for changes in the composition, pressure and temperature of that fluid in a flowmeter having a first dynamic microbridge exposed to the flow and producing a flow-related output signal, the apparatus characterised by:

(A) means to obtain an uncorrected dynamic microbridge sensor output (G) for the fluid of interest;

(B) means to obtain the specific heat (c_{pe}) thermal conductivity (k_e) and temperature (T_e) of the fluid of interest;

(C) means to apply a gauge correction factor (C_G) to G to obtain a corrected sensor output (G_c), said C_G being determined according to a known relationship among values of specific heat (C_{pe}) thermal conductivity (k_e) and temperature (T_e) of the fluid of interest normalised with respect to a reference gas;

(D) means to obtain an uncorrected volumetric flow value (V) for the fluid of interest in relation to the corrected sensor output, G_c;

(E) means to apply a volumetric correction factor (C_V) to the flow value (V) to obtain the corrected volumetric flow value (V_c), C_V being determined according to a known relationship, among values of specific heat (C_{pe}), thermal conductivity (k_e) and temperature (T_e) of the fluid of interest normalised with respect to the reference gas.

13. Apparatus according to Claim 12 characterised by means to determine the gauge correction factor according to a relationship selected from:

$$C_G = (k_e/k_{co})^{n1}(c_{pe}/c_{pco})^{n2}(T_e/T_c)^{n3}$$

or

$$1/C_G = \{(A_0 + k_e)/(A_0 + k_{co})\}^{n1} \{(B_0 + c_{pe})/(B_0 + c_{pco})\}^{n2} \{T_e/T_c\}^{n3}$$

or

$$1/C_G = \{(A_0 + A_1 k_e^{m1} + A_2 k_e^{m2} + \ldots) / (A_0 + A_1 k_{co}^{m1} + A_2 k_{co}^{m2} + \ldots)\}^{n1}$$

$$\{(B_0 + B_1 c_{pe}^{p1} + B_2 c_{pe}^{p2} + \ldots) / (B_0 + B_1 c_{pco}^{p1} + \ldots)\}^{n2} \{T_e/T_c\}^{n3}$$

and the volumetric correction factor (C_V) is determined according to a relationship selected from:

$$C_V = (k_e/k_{co})^{n4}(c_{pe}/c_{pco})^{n5}(T_e/T_c)^{n6}$$

or

$$1/C_V = \{(C_0 + k_e)/(C_0 + k_{co})\}^{n4} \{(D_0 + c_{pe})/(D_0 + c_{pco})\}^{n5} \{T_e/T_c\}^{n6}$$

or

$$1/C_V = \{(c_0 + c_1 k_e{}^{q_1} + c_2 k_e{}^{q_2} + \ldots)/$$

$$(c_0 + c_1 k_{co}{}^{q_1} + c_2 k_{co}{}^{q_2} + \ldots)\}^{n_4}$$

$$\{(D_0 + D_1 c_{pe}{}^{r_1} + \ldots)/(D_0 + D_1 c_{pco}{}^{r_1} + \ldots)\}^{n_5}$$

$$\{T_e/T_c\}^{n_6}$$

Where:

n_1 through n_6, A_i, B_i, m_i, c_i,

D_i, q_i, and r_i = constants determined by the calibration process, and

K_{co}, c_{pco} and T_c = thermal conductivity, specific heat and temperature of the calibration gas.

14. Apparatus according to Claim 12 or 13 characterised by means to determine the gauge correction factor according to the relationship:

$$C_G = (k_e/k_{co})^{n_1}(c_{pe}/c_{pco})^{n_2}(T_e/T_c)^{n_3}$$

and the volumetric correction factor C_V is determined according to the relationship:

$$C_V = (k_e/k_{co})^{n_4}(c_{pe}/c_{pco})^{n_5}(T_e/T_c)^{n_6}$$

and n_1 through n_6, respectively, are approximately equal to:

- 0.015331
- 0.060124
  0.387617
- 0.85033
  0.9845898
  0.027236

15. Apparatus for compensating the mass flow measurement of a gaseous fluid of interest for changes in the composition, pressure and temperature of that fluid in a flowmeter having a first dynamic microbridge exposed to the flow and producing a flow-related output signal, the apparatus characterised by:

(A) means to obtain an uncorrected dynamic microbridge sensor output (G) for the fluid of interest;

(B) means to obtain the specific heat (c_{pe}) thermal conductivity (k_e) and temperature (T_e) of the fluid of interest;

(C) means to apply a gauge correction factor (C_G) to G to obtain a corrected sensor output (G_C), said C_G being determined according to a known relationship among values of specific heat (c_{pe}) thermal conductivity (k_e) and temperature (T_e) of the fluid of interest normalized with respect to a reference gas;

(D) means to obtain an uncorrected mass flow value (M) for the fluid of interest in relation to the corrected gauge output (G_C);

(E) means to apply a mass correction factor (C_M) to the mass flow value to obtain the corrected mass flow value (M_C), C_M being determined according to a known relationship, among values of specific heat (c_{pe}), thermal conductivity (k_e) and temperature (T_e) of the fluid of interest normalized with respect to the reference gas.

16. Apparatus according to Claim 15 characterised by means to determine the gauge correction factor according to a relationship selected from:

$$C_G = (k_e/k_{co})^{n_1}(c_{pe}/c_{pco})^{n_2}(T_e/T_c)^{n_3}$$

or

$$1/C_G = \{(A_0 + k_e)/(A_0 + k_{co})\}^{n_1} \{(B_0 + c_{pe})/(B_0 + c_{pco})\}^{n_2} \{T_e/T_c\}^{n_3}$$

or

$$1/C_G = \{(A_0 + A_1 k_e^{m_1} + A_2 k_e^{m_2} + \ldots)/$$

$$(A_0 + A_1 k_{co}^{m_1} + A_2 k_{co}^{m_2} + \ldots)\}^{n_1}$$

$$\{(B_0 + B_1 c_{pe}^{p_1} + B_2 c_{pe}^{p_2} + \ldots) /$$

$$(B_0 + B_1 c_{pco}^{p_1} + \ldots)\}^{n_2} \{T_e/T_c\}^{n_3}$$

and the mass correction factor (C_M) is determined according to a relationship selected from:

$$C_M = (k_e/k_{co})^{n_4}(c_{pe}/c_{pco})^{n_5}(T_e/T_c)^{n_6}$$

or

$$1/C_M = \{(C_0 + k_e)/(C_0 + k_{co})\}^{n_4} \{(D_0 + c_{pe})/(D_0 + c_{pco})\}^{n_5} \{T_e/T_c\}^{n_6}$$

or

$$1/C_M = \{(C_0 + C_1 k_e^{q_1} + C_2 k_e^{q_2} + \ldots)/$$

$$(C_0 + C_1 k_{co}^{q_2} + C_2 k_{co}^{q_2} + \ldots)\}^{n_4}$$

$$\{(D_0 + D_1 c_{pe}^{r_1} + \ldots)/(D_0 + D_1 c_{pco}^{r_1} + \ldots)\}^{n_5}$$
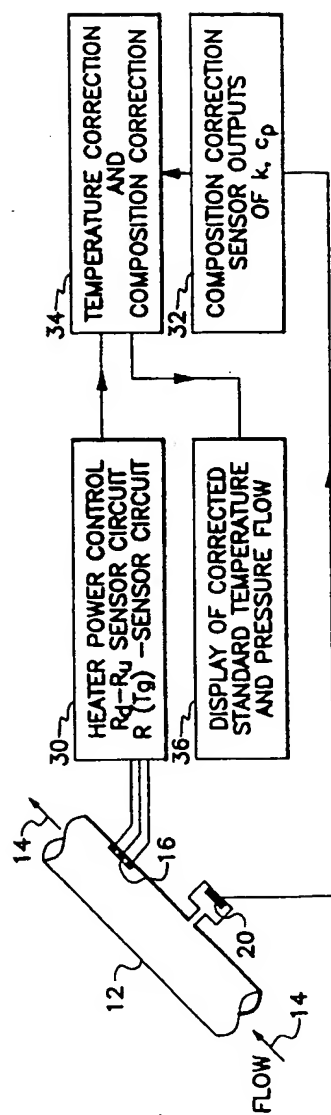
$$\{T_e/T_c\}^{n_6}$$

Where:

n_1 through n_6, A_i, B_i, m_i, c_i,

D_i, q_i, and r_i = constants determined by the calibration process, and

K_{co}, c_{pco} and T_c = thermal conductivity, specific heat and temperature of the calibration gas.

17. Apparatus for compensating the energy flow measurement of a gaseous fluid of interest for changes in the composition, pressure and temperature of that fluid in a flowmeter having a first dynamic microbridge exposed to the flow and producing a flow-relating output signal, the apparatus characterised by:

(A) means to obtaining an uncorrected dynamic microbridge sensor output (G) for the fluid of interest;

(B) means to obtain the specific heat (c_{pe}) thermal conductivity (k_e) and temperature (T_e) of the fluid of interest;

(C) means to apply a gauge correction factor (C_G) to G to obtain a corrected sensor output (G_C), said C_G being determined according to a known relationship among values of specific heat (c_{pe}) thermal conductivity (k_e) and temperature (T_e) of the fluid of interest normalized with respect to a reference gas;

(D) means to obtain an uncorrected energy flow value (E) for the fluid of interest in relation to the corrected gauge output (G_C) ;

(E) means to apply an energy correction factor (C_E) to the flow value to obtain the corrected energy flow value, (E_C), C_E being determined according to a known relationship, among values of specific heat (c_{pe}), thermal conductivity (k_e) and temperature (T_e) of the fluid of interest normalized with respect to the reference gas.

18. Apparatus according to Claim 17 characterised by means to determine the gauge correction factor according to a relationship selected from:

$$C_G = (k_e/k_{co})^{n_1}(c_{pe}/c_{pco})^{n_2}(T_e/T_c)^{n_3}$$

or

$$1/C_G = \{(A_0 + k_e)/(A_0 + k_{co})\}^{n_1} \{(B_0 + c_{pe})/(B_0 + c_{pco})\}^{n_2} \{T_e/T_c\}^{n_3}$$

or

$$1/C_G = \{(A_0 + A_1k_e{}^{m_1} + A_2k_e{}^{m_2} + \ldots)/$$

$$(A_0 + A_1k_{co}{}^{m_1} + A_2k_{co}{}^{m_2} + \ldots)\}^{n_1}$$

$$\{(B_0 + B_1c_{pe}{}^{p_1} + B_2c_{pe}{}^{p_2} + \ldots)/$$

$$(B_0 + B_1c_{pco}{}^{p_1} + \ldots)\}^{n_2}\{T_e/T_c\}^{n_3}$$

and the energy correction factor (C_E) is determined according to a relationship selected from:

$$C_E = (k_e/k_{co})^{n_4}(c_{pe}/c_{pco})^{n_5}(T_e/T_c)^{n_6}$$

or

$$1/C_E = \{(C_0 + k_e)/(C_0 + k_{co})\}^{n_4}\{(D_0 + c_{pe})/(D_0 + c_{pco})\}^{n_5}\{T_e/T_c\}^{n_6}$$

or

$$1/C_E = \{(C_0 + C_1k_e{}^{q_1} + C_2k_e{}^{q_2} + \ldots)/$$

$$(C_0 + C_1k_{co}{}^{q_1} + C_1k_{co}{}^{q_2} + \ldots)\}^{n_4}$$

$$\{(D_0 + D_1c_{pe}{}^{r_1} + \ldots)/(D_0 + D_1c_{pco}{}^{r_1} + \ldots)\}^{n_5}$$

$\{T_e/T_c\}^{n_6}$

Where:

n_1 through n_6, A_i, B_i, m_i, c_i,

D_i, q_i, and r_i = constants determined by the calibration process, and

K_{co}, c_{pco} and T_c = thermal conductivity, specific heat and temperature of the calibration gas.

19. Apparatus according to any of Claims 12 to 18 characterised by a second microbridge, in relatively static communication with said fluid of interest, to determine c_{pe}, k_e and T_e.

20. Apparatus according to any of Claims 12 to 19 characterised in that the means to apply C_G in step (C) comprises means to determine C_G according to a known relationship among variables selected from the group consisting of specific heat (c_{pe}), the differential of specific heat with respect to temperature (dc_{pe}/dT), thermal conductivity (k_e), the differential of thermal conductivity with respect to temperature (dk_e/dT), density, viscosity, speed of sound, optical absorption or diffusibility.

BLOCK DIAGRAM OF PROPOSED
TEMPERATURE AND/OR PRESSURE
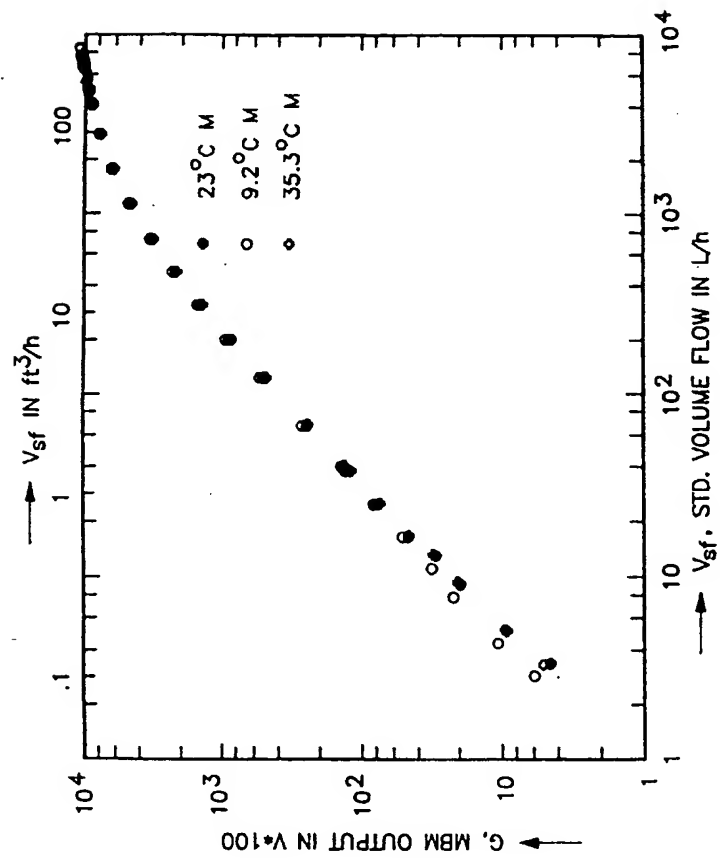COMPENSATION FOR MB FLOW SENSORS

Fig. 1

Fig. 2   MB GAS SENSOR OUTPUT VS. STD. FLOW
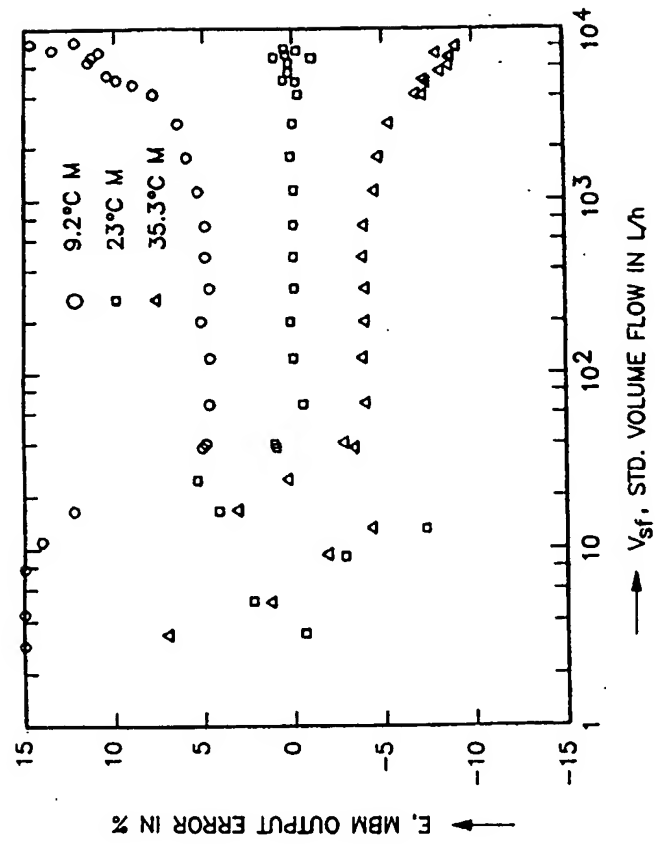FOR SEVERAL GAS TEMPERATURES

Fig. 3 MB GAS SENSOR ERROR VS. STD. FLOW
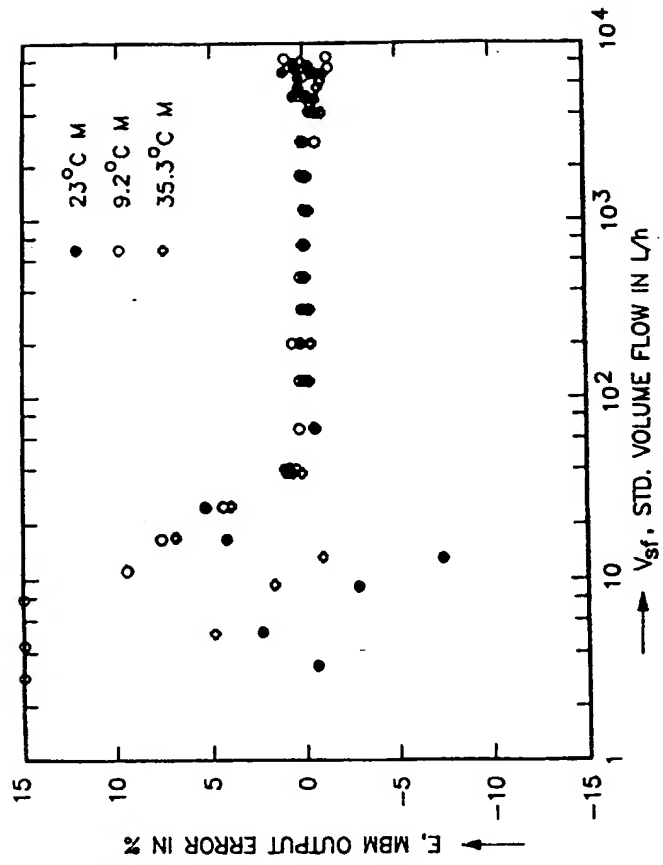FOR SEVERAL METHANE TEMPERATURES

Fig. 4   MB GAS SENSOR ERROR VS. STD. FLOW
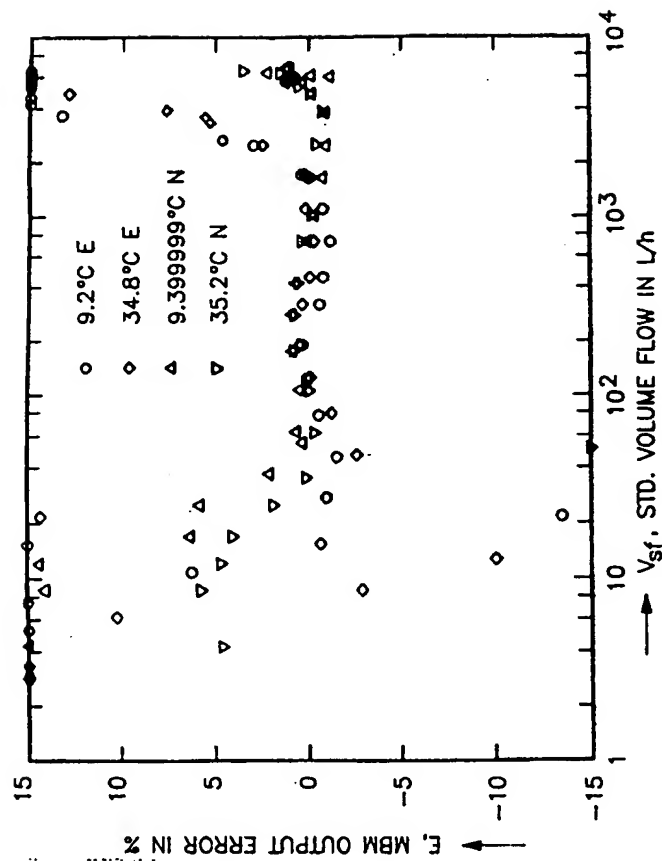FOR SEVERAL GAS TEMPEATURES

Fig. 5   MB GAS SENSOR ERROR VS. STD. FLOW
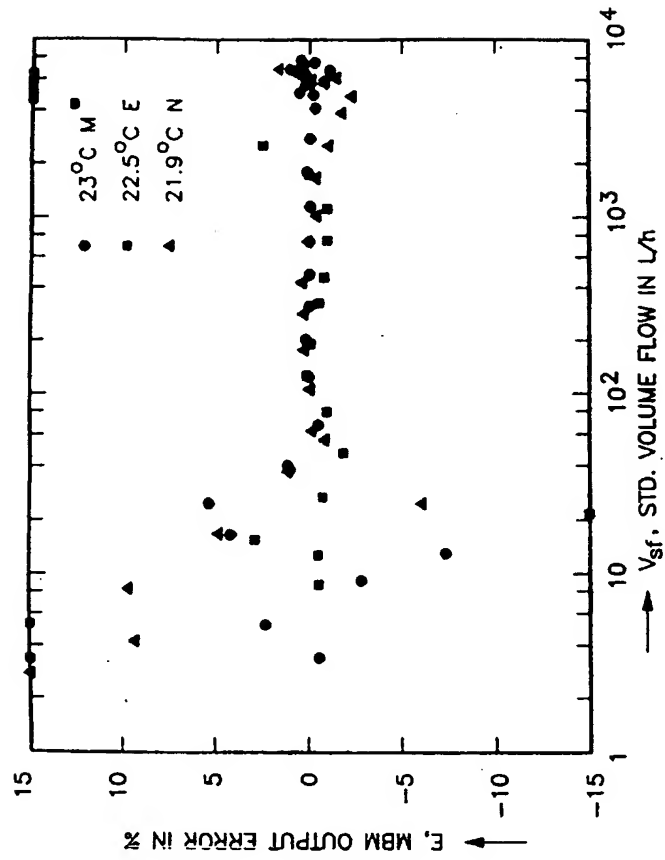FOR SEVERAL GASES AND TEMPERATURES

Fig. 6 MB GAS SENSOR ERROR VS. STD. FLOW FOR
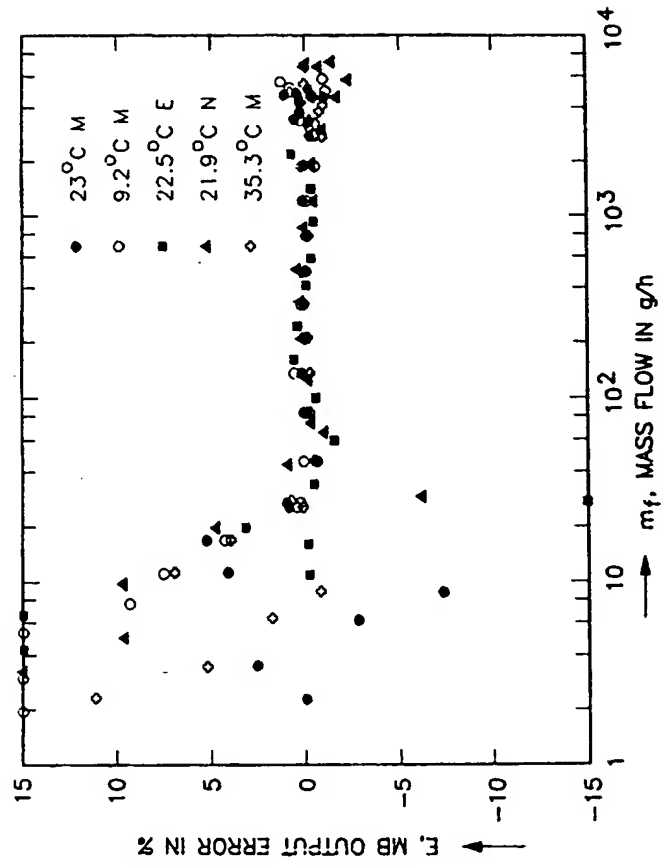SEVERAL GASES AT ROOM TEMPERATURE

Fig. 7

MICROBRIDGE SENSOR ERROR VS. MASS FLOW,
FOR VARIOUS GASES, AFTER COMPENSATION.
REFERENCE GAS CALIBRATION TEMPERATURE OF 23°C